Releasing more capacity for EV integration by DC medium voltage distribution lines

Lu Zhang[1], Ying Chen[1], Chen Shen[1] ✉, Wei Tang[2], Jun Liang[3]

[1]Department of Electrical Engineering, Tsinghua University, Beijing, People's Republic of China

[2]College of Information and Electrical Engineering, China Agricultural University, Beijing, People's Republic of China

[3]School of Engineering, Cardiff University, Cardiff CF24 3AA, UK

✉ E-mail: shenchen@mail.tsinghua.edu.cn

Abstract: With the integration of large-scale electric vehicles (EVs), more capacities of medium voltage distribution networks need to be released. However, there are limited spaces to build new lines, and voltage violation may happen due to the power fluctuation when EVs charge/discharge in a random way. This study proposes to convert some existing AC medium voltage distribution lines to DC and forms a hybrid AC/DC medium voltage distribution network through connecting existing AC lines with a voltage source converter (VSC). Transfer capacity of lines can be increased through DC distribution and flexible power shift between the AC and DC lines can be achieved, based on which more EVs can be accommodated. Configurations of hybrid AC/DC distribution networks are developed, and the capacities released are quantified. A control scheme, which includes a loss minimisation mode and a voltage regulation mode, is proposed in order to optimise real and reactive power outputs of the VSC. Simulation studies are performed to verify the proposed method.

1 Introduction

Medium voltage distribution network will face several challenges with the integration of large-scale electric vehicles (EVs), which may cause severe voltage drops [1], over voltages [2], overloading of lines [3], and high losses [4] because EVs have random activities.

Various control methods have been proposed to alleviate these probabilistic impacts [5–14]. The authors in [5–11] proposed coordination methods for EV charging strategies in distribution networks considering distribution grid constraints including distribution line thermal ratings, transformer capacities, and voltage limits. Weckx *et al.* [1] presented a market-based multi-agent control mechanism of EVs, which incorporates distribution transformers and voltage constraints. Hoog *et al.* [12] extended [1] by explicitly taking into account underlying network constraints at the distribution level. Ardakanian *et al.* [13] proposed a real-time distributed charging algorithm, and addressed the line and transformer congestion arising from uncontrolled charging of EVs. Zhao *et al.* [14] proposed to determine the largest admissible charging demand at each distribution network node that can be accommodated, in order to ensure voltages and line capacity within operation limits. Existing methods were mainly focused on the optimisation of EV charging strategy under the constraints of distribution networks.

However, only considering EV charging patterns and customer side improvement, which can be achieved through existing methods, are not enough due to the constraints of line capacities and node voltages. Also, line capacity is not fully utilised flexibly because EV charging is in a random way. Power shift between two adjacent distribution lines so as to increase overall power transfer capacities might be a way to meet the operation requirement of accommodating large-scale EVs. However, AC medium voltage distribution lines are normally operated as a radial network, because closed-loop operation in AC distribution networks will cause circulating currents due to different phase angles or amplitudes.

Network reconfiguration in distribution network is an important way to achieve load transfer between two feeders, based on which both transfer capacity and EV hosting capacity can be increased. However, operation costs will increase because of frequent switching of circuit breakers (CBs) [15]. Therefore, it is very difficult to achieve real-time optimal power transfer in AC distribution networks through network reconfiguration.

To circumvent this issue, some papers proposed to use power electronic devices in distribution networks [16, 17]. Cao *et al.* [16] proposed to adopt a back-to-back converter in a distribution network to reduce power losses and improve node voltage profiles. Sciano [17] utilised a short DC line to connect heavily meshed urban distribution networks to increase operational flexibility. Through the above references, we do see power electronic devices help AC distribution networks achieve flexible power transfer. However, DC links of these power electronic devices are not utilised for load supply and EV integrations. The maximum transfer power capacity of each AC line is not increased.

DC technology has been proposed to integrate electrical vehicles [18, 19], improve power quality [20], increase transfer capacities [21], and reduce losses [22]. Development of electric and electronic technologies offers great possibilities for DC distribution networks. DC technology has been used in high voltage transmission networks [23] and low voltage microgrids [24], but has not yet attracted attentions in medium voltage distribution networks. In addition to building a new DC network, existing AC lines in medium voltage distribution networks can be converted to DC lines through converters [25]. AC lines and DC lines will exist in distribution networks simultaneously and form hybrid AC/DC medium voltage distribution networks.

The hybrid AC/DC medium voltage distribution network can achieve flexible power shift through voltage source converters (VSCs), based on which transfer power capacities of all lines can be fully used. Constraints of medium voltage distribution networks can be released taking the advantages of DC lines. By rescheduling power between lines, cost-effective operation can be achieved when one line is facing the risk of voltage violation, overloading, and high losses due to the integration of large-scale random EVs.

Ahmed *et al.* [26] proposed a planning approach for the network configuration of AC–DC hybrid distribution systems, in which genetic algorithm is used to search for optimal AC–DC configurations. Eajal *et al.* [27] presented a two-stage stochastic centralised dispatch scheme for AC/DC hybrid smart grids. However, the benefits of DC operation in the distribution network have not been fully analysed. Especially, the EV accommodation capabilities in hybrid AC/DC medium voltage distribution network have not been quantified.

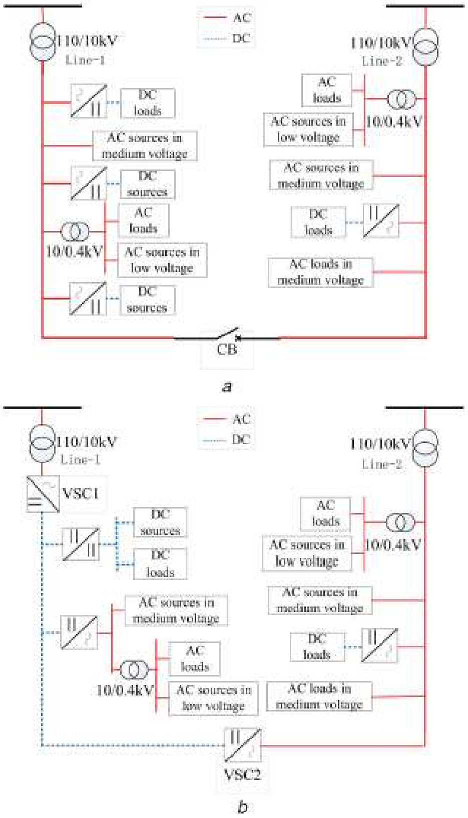

Fig. 1 *Medium voltage distribution network*
(a) Traditional structure of medium voltage distribution network, ***(b)*** Hybrid AC/DC medium voltage distribution network

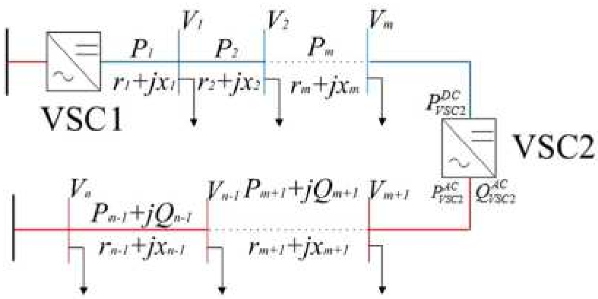

Fig. 2 *Power injection model of a hybrid AC/DC medium voltage distribution network*

In this paper, in order to release more capacities for EV integration, some AC lines are proposed to be converted to DC ones, and a hybrid AC/DC medium voltage distribution network is formed through connecting existing AC lines with VSCs. Different configurations of DC lines, which are converted from three-phase AC lines, are analysed. The increased capacity for EV integration is quantified. A control scheme of hybrid AC/DC medium voltage distribution networks is proposed for EV integration through flexible power shift between AC lines and DC lines.

The main contents of this work are organised as follows. Section 2 describes the main technique issues related to accommodating EV integration by transferring an AC distribution grid to a hybrid AC/DC one. In Section 3, a variety of ways for converting AC links to DC ones are introduced and compared. Then, in order to maximise EV accommodation, an optimisation control scheme is proposed for such a hybrid AC/DC medium voltage distribution network. Section 5 presents case studies with result discussions. Section 6 concludes the paper finally.

2 Problem description

Fig. 1*a* illustrates a traditional medium voltage distribution network, where two feeders from different substations are interconnected through a normally opened CB. Fig. 1*b* illustrates a hybrid AC/DC medium voltage distribution network structure, where an AC line (line 1) is converted to DC through a VSC (VSC1), and the CB is replaced by a VSC (VSC2) to interconnect the AC and DC lines.

VSC2 can control reactive and active power independently [28]. Reactive power can be injected into AC lines, so reactive power demands in an AC line can be compensated locally. Therefore, investment and operation costs of var/voltage devices can be reduced, node voltage deviations can be eliminated, and losses can be decreased because less reactive power flow in the AC line.

It is assumed that (i) in the AC line, voltage of the secondary sides of distribution transformers is fixed as 1.02 p.u.; (ii) with the increasing capacities of integrated EVs, voltage violations could happen during day-ahead optimisation due to limited thermal ratings of distribution lines, as well as the switching times of CB in a day [15]; (iii) voltage violations could happen in real time as the day-ahead optimisation is based on probabilistic forecasts of load demands and EV charging and discharging.

Thus, this paper proposes to convert some AC medium voltage lines to DC lines as shown in Fig. 2, and form hybrid AC/DC medium voltage distribution networks. An optimal control scheme, including day-ahead optimisation and real-time regulation, is therefore needed in hybrid AC/DC medium voltage distribution networks in order to optimise the references of the active and reactive power of VSC2 to achieve EV accommodation maximisation, loss minimisation, and voltage profile improvement.

Fig. 2 illustrates the real and reactive power injections of a hybrid AC/DC medium voltage distribution network.

The real and reactive power injections at both terminals are specified as the decision variables, which are $P^{\rm DC}_{\rm VSC2}$ and $Q^{\rm AC}_{\rm VSC2}$. $P^{\rm AC}_{\rm VSC2}$ is not included because it is determined by $P^{\rm DC}_{\rm VSC1}$ and VSC loss, which can be represented as $P^{\rm DC}_{\rm VSC2} = P^{\rm AC}_{\rm VSC2} + P^{\rm VSC}_{\rm loss}$.

An optimal control scheme of hybrid AC/DC medium voltage distribution networks is developed to determine $P^{\rm AC}_{\rm VSC2}$ and $Q^{\rm AC}_{\rm VSC2}$.

The optimal scheme includes a day-ahead loss reduction mode and a real-time voltage regulation mode. The loss reduction mode is to obtain optimal references of VSC2 for a day, aimed at reducing power losses while considering constraints of hybrid AC/DC medium voltage distribution networks. The voltage regulation mode is a real-time refinement aimed at keeping node voltages within a security range in case of sudden changes of EV charging/discharging and abrupt load changes.

The loss reduction mode is performed once every day in day-ahead based on forecasted values of loads and EVs, in order to obtain optimal hourly active and reactive power output of $P^{\rm AC}_{\rm VSC2}$ and $Q^{\rm AC}_{\rm VSC2}$ of VSC2 for next 24 h. The optimal problem in the loss reduction mode is solved by genetic algorithm, which is suitable for searching a global optimum [29].

During real-time voltage regulation, when VSC2 transfers power to a distribution line, the voltage changes in all network nodes, but some nodes' voltages vary more than others due to the power injection. This influence can be obtained using a sensitivity method [30]. Distribution lines are short compared with transmission lines, so the error of sensitivity methods, which is mainly determined by resistance and reactance of lines, is small. Therefore, a voltage-sensitivity approach is used in the voltage regulation mode, which optimises $P^{\rm AC}_{\rm VSC2}$ and $Q^{\rm AC}_{\rm VSC2}$ of VSC2 to regulate node voltages in every short time interval using latest measurements, in order to mitigate the voltages violations caused by forecast errors of EVs and loads.

These two control modes are cooperated with each other following an event-driven rule. The optimal results of loss reduction mode are applied if all nodes voltages are within a security range. The voltage regulation mode is triggered if a node voltage is hitting the limit due to unexpected power fluctuations in real time. Voltage security range is set as (0.95–1.05 p.u.), while the node voltage is required to be within (0.93–1.07 p.u.) [31].

Configuration	AC	DC	
		Symmetrical with neutral line	Asymmetrical
Layout			
$P_{\max}$	$2\sqrt{3}U_{AC} \cdot I_{AC}\cos\varphi$	$\sqrt{3}U_{AC} \cdot I_{AC}\cos\varphi + 2U_{DC}I_{DC}$	$\sqrt{3}U_{AC} \cdot I_{AC}\cos\varphi + 3U_{DC}I_{DC}$
$P_{\max}$ ratio	1	1.029	1.294

Fig. 5 *Double circuit overhead wire (convert one AC circuit to DC)*

Configuration	AC	DC	
		Symmetrical with neutral line	Symmetrical without neutral conductors
Layout			
$P_{\max}$	$2\sqrt{3}U_{AC} \cdot I_{AC}\cos\varphi$	$4U_{DC}I_{DC}$	$6U_{DC}I_{DC}$
$P_{\max}$ ratio	1	1.058	1.587

Fig. 6 *Double circuit overhead wire (convert both AC circuits to DC)*

Therefore, the resistance of an AC line is about 1.021 times of that in a DC line, if taking a typical conductor in medium voltage distribution networks.

Considering the same heat dissipation capability of a conductor, $I_{\mathrm{DC}}^2 r_{\mathrm{DC}} = I_{\mathrm{AC}}^2 r_{\mathrm{AC}}$, thus $I_{\mathrm{DC}} = 1.01 I_{\mathrm{AC}}$.

Moreover, an AC line carries more or less reactive power, assuming a typical power factor $\cos\varphi = 0.9$.

Figs. 4–6 give the ratio of the maximum transfer capacity of a line to that of an AC line ($P_{\max-\mathrm{ratio}} = P_{\max}/P_{\max-\mathrm{AC}}$), which in Fig. 4 are 1.058 for a symmetrical configuration of VSC with neutral line, 2.116 for a symmetrical configuration of VSC without neutral line, and 1.587 for an asymmetrical configuration of VSC. Therefore, the symmetrical configuration of VSC without a neutral line is chosen in order to maximise the released capacities of existing lines. Moreover, the current in the neutral conductor may be too large for the asymmetrical configuration with three conductors.

3.2 Network losses

The maximum losses of an AC and DC line should be the same due to the heat dissipation capability of a conductor, so losses are compared with the same transfer capacity P_N.

Losses in an AC distribution line can be calculated as

$$P_{\mathrm{loss}}^{\mathrm{AC}} = \frac{P_N^2 + Q_N^2}{U_{\mathrm{AC}}^2} r_{\mathrm{AC}} \tag{5}$$

where P_N and Q_N are active and reactive power in distribution lines.

Losses in a DC line can be calculated as

$$P_{\mathrm{loss}}^{\mathrm{DC}} = \frac{P_N^2}{U_{\mathrm{DC}}^2} r_{\mathrm{DC}} \tag{6}$$

In a DC distribution line, all the allowable current can be used to transfer real power with very little reactive power.

The loss of a DC line is about one-third of that of an AC line, if taking a typical power factor 0.9 under the same power conductors.

3.3 Voltage drop

An AC voltage drop under the maximum power transfer $P_{\max}$ can be calculated as

$$\Delta U_{\mathrm{AC}} = \frac{P_{\max} \cdot r_{\mathrm{AC}} + Q_{\max} \cdot x_{\mathrm{AC}}}{U_{\mathrm{AC}}} \tag{7}$$

where r and x are resistance and reactance, respectively.

A DC voltage drop can be calculated as

$$\Delta U_{\mathrm{DC}} = \frac{P_{\max}}{U_{\mathrm{DC}}} r_{\mathrm{DC}} \tag{8}$$

The voltage drop of DC lines is about half of that in AC lines, assuming r/x ratio is 1.7, which is a typical parameter of overhead wire in the medium voltage distribution network.

4 Optimisation scheme of hybrid AC/DC medium voltage distribution network for EV accommodation

4.1 Loss reduction mode

$$\min F_{\mathrm{normal}} = P_{\mathrm{loss}} \tag{9}$$

$$P_{\mathrm{loss}} = P_{\mathrm{loss}}^{\mathrm{DC}} + P_{\mathrm{loss}}^{\mathrm{AC}} + P_{\mathrm{loss}}^{\mathrm{VSC}} \tag{10}$$

where P_{loss} is the total losses of the hybrid AC/DC medium voltage distribution network; $P_{\mathrm{loss}}^{\mathrm{DC}}$ and $P_{\mathrm{loss}}^{\mathrm{AC}}$ are losses of DC and AC medium voltage distribution lines, respectively; $P_{\mathrm{loss}}^{\mathrm{VSC}}$ is loss of VSC1, VSC2, and VSCs for connecting AC loads to DC lines. $P_{\mathrm{loss}}^{\mathrm{VSC}}$ is calculated using a generalised loss equation (11) [33]

$$P_{\mathrm{loss}}^{\mathrm{VSC}} = a + b \cdot I_c + c \cdot I_c^2 \tag{11}$$

Subject to

$$S_{ij}^{\mathrm{DC}} \le S_{\max}^{\mathrm{DC}} \tag{12}$$

$$S_{ij}^{\mathrm{AC}} \le S_{\max}^{\mathrm{AC}} \tag{13}$$

$$\sqrt{P_{\mathrm{vsc}}^2 + Q_{\mathrm{vsc}}^2} \le S_{\max}^{\mathrm{vsc}} \tag{14}$$

$$U_{\min} \le U_i \le U_{\max} \tag{15}$$

$$\begin{cases} P_i = U_i \sum_{j=1}^{N} U_j (G_{ij}\cos\theta_{ij} + B_{ij}\sin\theta_{ij}) \\ Q_i = U_i \sum_{j=1}^{N} U_j (G_{ij}\sin\theta_{ij} - B_{ij}\cos\theta_{ij}) \end{cases} \tag{16}$$

where S_{ij}^{DC} and S_{ij}^{AC} are power flow of DC and AC lines in branch ij, respectively; $S_{\max}^{\mathrm{DC}}$ and $S_{\max}^{\mathrm{AC}}$ are allowable maximum power flow of DC and AC lines, respectively; $U_i^{\min}$, $U_i^{\max}$ are allowable minimum voltage value, allowable maximum voltage value of node i, respectively; P_i, Q_i are active and reactive power injection of bus i; U_i and U_j are voltages of i and j; n is node number; G_{ij} and B_{ij} are real part and imaginary part of admittance matrix, δ_{ij} is difference of phase angles i and j, respectively.

4.2 Voltage regulation mode

A sensitivity theory is used in this mode. The objective is to keep node voltages within a security range. The sensitivity of voltage to active power and reactive power can be obtained through resistance and reactance of node contained path [30]

$$S_P = \frac{\partial U_i}{\partial P_j} = -\frac{R_{i,\mathrm{VSC2}}}{U_n} \tag{17}$$

$$S_Q = \frac{\partial U_i}{\partial Q_j} = --\frac{X_{i,\mathrm{VSC2}}}{U_n} \tag{18}$$

where U_n is rated voltage, $R_{i,\mathrm{VSC2}}$ and $X_{i,\mathrm{VSC2}}$ are resistance and reactance between node i and VSC2. S_Q is only applied for AC side.

The sensitivities of node voltages to active power in DC lines can be represented as

$$[\Delta U^{\mathrm{DC}}] = [S_P^{\mathrm{DC}}] \cdot [\Delta P] \tag{19}$$

where S_P^{DC} is the voltage sensitivities to active power in the DC line.

The sensitivities of node voltages to active power and reactive power in AC lines can be represented as

$$[\Delta U^{\mathrm{AC}}] = [S_P^{\mathrm{AC}}] \cdot [\Delta P] + [S_Q^{\mathrm{AC}}] \cdot [\Delta Q] \tag{20}$$

where S_P^{AC} and S_Q^{AC} are the voltage sensitivities to active and reactive power, respectively, in the AC line.

Therefore, a sensitivity equation of hybrid AC/DC distribution network can be represented as (21) by combining (19) and (20)

$$\begin{bmatrix} \Delta U_1 \\ \vdots \\ \Delta U_m \\ \Delta U_{m+1} \\ \vdots \\ \Delta U_n \end{bmatrix} = \begin{bmatrix} S_P^{\mathrm{DC}1} \\ \vdots \\ S_P^{\mathrm{DC}m} \\ S_P^{\mathrm{AC}m+1} \\ \vdots \\ S_P^{\mathrm{AC}n} \end{bmatrix} \cdot [\Delta P_m] + \begin{bmatrix} 0 \\ \vdots \\ 0 \\ S_Q^{\mathrm{AC}m+1} \\ \vdots \\ S_Q^{\mathrm{AC}n} \end{bmatrix} \cdot [\Delta Q_{m+1}] \tag{21}$$

where ΔP_m is power adjustment of VSC2 at the DC side, which is equal to the real power adjustment of VSC2 at the AC side ΔP_{m+1}; ΔQ_{m+1} is the reactive power adjustment of VSC2 at the AC side.

First, if an AC node voltage is higher than 1.05 p.u. or lower than 0.95 p.u., reactive power of VSC2 is used to regulate the voltage because the DC line is not affected by the reactive power regulation of the AC side. Equation (22) is used to calculate the adjustment of VSC2 reactive power output based on the maximum voltage deviation of the measured nodes ΔU_i

$$\Delta Q = \Delta U_i / S_Q^{\mathrm{AC}i} \tag{22}$$

where $S_Q^{\mathrm{AC}i}$ is the corresponding sensitivity of node i.

Second, if the node voltage is still higher than 1.05 p.u. or lower than 0.95 p.u. when VSC2 reactive power has reached its maximum value under the power rating limit of the converter, then both active and reactive power of VSC2 will be used to regulate the node voltage. Equation (23) is used to calculate the adjustment of VSC active and reactive power outputs based on ΔU_i

$$\begin{cases} S_P^{\mathrm{AC}i} \cdot \Delta P + S_Q^{\mathrm{AC}i} \cdot \Delta Q = \Delta U_I \\ (P_{\mathrm{VSC2}}^{\mathrm{AC}} + \Delta P)^2 + (Q_{\mathrm{VSC2}}^{\mathrm{AC}} + \Delta Q)^2 = S_{\max}^{\mathrm{VSC2}} \end{cases} \tag{23}$$

There will be two real solutions in quadratic equations (23), and the smaller solution of ΔP is chosen, in order to reduce the effect on node voltages in the DC line.

If a DC node voltage is higher than 1.05 p.u. or lower than 0.95 p.u., active power of VSC2 is used to regulate the node voltages based on the following equation:

$$\Delta P = \Delta U_i / S_P^{\mathrm{DC}i} \tag{24}$$

The absolute value of VSC2 reactive power will be reduced in order to release the rating of VSC2 for active power to regulate node voltages (no matter the node is in the AC line or in the DC line) if active power is limited by current rating of VSC2, and (23) is used to calculate the adjustments.

5 Case study

Two case studies were conducted to demonstrate the superiority of a hybrid AC/DC medium voltage distribution on EVs accommodation, which is formed through converting AC medium voltage lines to DC ones.

5.1 Simulation background

A traditional AC 16-node medium voltage distribution network with EVs is shown in Fig. 7*a*, in which two double-circuit medium voltage lines are interconnected through a normally opened CB. Loads are 8 MW, and the rated capacities of EVs are 1 MW. In order to release more capacity for EV integration, three-phase AC wires of line-1 are converted to a symmetrical DC without neutral conductors, based on which transfer capacities are expected to increase about 58.7% as discussed in Section 3. Line-2 remains as a medium voltage AC line, and connect with line-1 through VSC, thus a hybrid AC/DC medium voltage distribution network is formed, as shown in Fig. 7*b*. Outputs of EVs remain as AC output as they were in the AC system. Direct DC connection or DC/DC converters can be used but not considered in this study. The rated capacity of VSC2 is 3 MW. The voltage of the secondary side of a distribution transformer is assumed to be 1.03 p.u.

Two conditions of loads and EVs are considered, as shown in Figs. 8*a* and *b*, respectively. In order to highlight the effectiveness of EV accommodation in the proposed hybrid AC/DC medium voltage distribution network, the penetration of EV is assumed to be 100% on the basis of loads, and fluctuations are exaggerated in study-2.

5.2 Study-1: increased EV charging and discharging capacities of hybrid AC/DC medium voltage distribution network

The voltage of AC distribution network is higher than 1.07 p.u. at 1 o'clock, as shown in Fig. 9*a*, because loads are light and the capacities of EV discharging are large. The voltage of AC

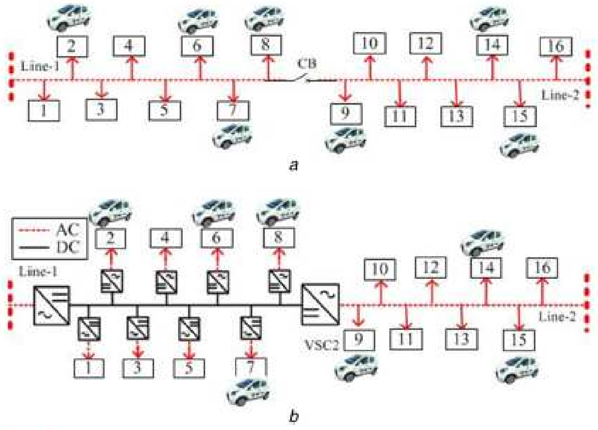

Fig. 7 *Medium voltage distribution networks with EVs*
(a) Traditional AC 16-node medium voltage distribution network with EVs, ***(b)*** Hybrid AC/DC medium voltage distribution network with EVs

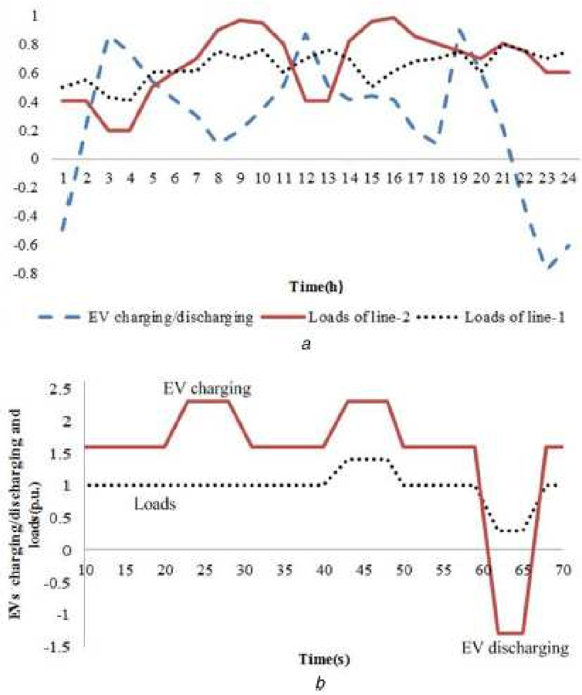

Fig. 8 *Backgrounds of studies*
(a) Loads and EVs outputs in 24 h for study-1, ***(b)*** Loads and EVs outputs in 70 s for study-2

Table 1 Loss comparisons

Case	Traditional AC distribution network	Hybrid AC/DC distribution network
power losses under base case	7351 kWh/day	3287 kWh/day

distribution network is lower than 0.93 p.u. at 19 o'clock because loads are heavy and the capacities of EV charging are large.

The voltage of node 8 is lower than 0.93 p.u., and loads may be shed at 19 o'clock, as shown in Fig. 9*b*. Voltages of all nodes are within the range of 0.93–1.07 p.u. after a network reconfiguration, because the load of node 6 is transferred to line-2. However, reconfiguration cannot transfer the loads between two lines frequently.

Voltages of all nodes are improved through converting line-1 to DC, and connecting two lines with the VSC2, because loads can be transferred between two lines flexibly.

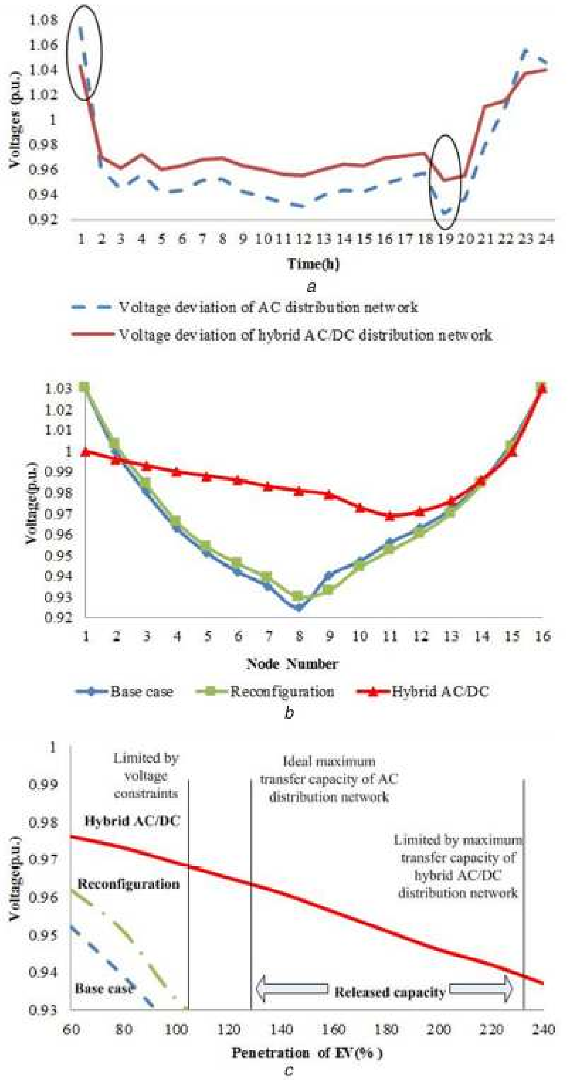

Fig. 9 *Results of study-1*
(a) Voltage deviations, ***(b)*** Node voltage profile at 19 o'clock, ***(c)*** Lowest node voltages under different penetration of EV charging

The maximum EV penetration is mainly determined by lowest node voltage and maximum allowable power of conductors. The maximum EV penetration of base case is about 87%, because the lowest node voltage is 0.93 p.u. when EV penetration increases to 87%, as shown in Fig. 9*c*. The maximum EV penetration increases to about 105% after network reconfiguration. The maximum EV penetration can be increased to about 235%, which is 2.7 times of the base case, and about 2.24 times of network reconfiguration, after converted to a hybrid AC/DC distribution network.

It should be noted that the main reason to limit transfer capacity is the maximum allowable power of conductors, which is different from the base case and reconfiguration case, because the lowest node voltage is about 0.94 p.u. as shown in Fig. 9*c*, the dashed red line.

Therefore, through converting the AC line to DC, about 99% (=235–136%) of EV penetration is increased compared with ideal maximum transfer capacity of AC distribution network, because more capacities are released. Actually, it is about 130% (=235–105%) because the maximum EV penetration is limited by voltage constraints, as shown in Fig. 9*c*.

Power losses in traditional AC distribution networks are 7351 kWh/day under base case, and the losses are 3287 kWh/day in the proposed hybrid AC/DC distribution network, which is reduced by 55.3% (Table 1). Such a remarkable loss reduction is resulted from optimal operations of DC links. As VSC2 can support reactive

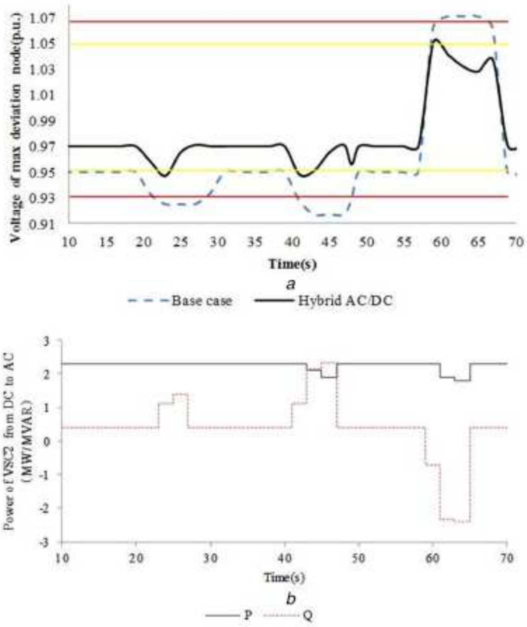

Fig. 10 *Results of study-2*
(a) Voltage deviation in 70 s, ***(b)*** Voltage deviation in 70 s

power for the connected AC line, power losses are reduced. Moreover, as the power flow in the distribution network is rescheduled optimally, the overall power losses are further reduced.

5.3 Study-2: increased EV accommodation considering the fluctuations of charging and discharging in hybrid AC/DC medium voltage distribution network

A real-time simulation was made to demonstrate the superiority of the proposed hybrid AC/DC distribution network on EVs accommodation, as shown in Fig. 10.

When charging/discharging power of EVs fluctuate as given in Fig. 8*b*, the node voltages in the base case experience low-voltage during 20–30 s, and 40–50 s, and over-voltage during 57–67 s, as shown in Fig. 10*a*. Reconfiguration cannot be used to prevent the overvoltage caused by frequent variation of EV charging/discharging power because rescheduling is slow and has limited numbers in each day. The proposed hybrid AC/DC medium voltage distribution network can help to keep node voltages within 0.93–1.07 p.u., as shown by the dashed black line in Fig. 10*a*.

When EV charging power increases during 20–30 s, VSC2 increases its reactive power output from the DC line to AC line because voltage regulation mode is triggered in order to keep node voltages within the security range, as shown in Fig. 10*b*.

When EV charging power further increases during 40–50 s, VSC2 reduces its real power in order to release more capacity for reactive power according to (23), then switches back to loss reduction mode at 47 s, when node voltage is regulated to over 0.97 p.u.

When EV discharging power increases significantly and loads decrease at the same time from 57 to 67 s, more reactive power needs to be absorbed from the AC line, while reducing the real power injected into the AC line can contribute to the voltage control and release more capacity for reactive power simultaneously. VSC2 reduces its real power to 1.8 MW at 63 s, and adjust its reactive power to −2.4 Mvar, based on which node voltages are regulated to the security range, and VSC2 switches back to loss reduction mode at 65 s, when its node voltage is between 0.97 and 1.03 p.u.

6 Conclusion

This paper proposed to form a hybrid AC/DC distribution network by converting existing AC lines to DC, in order to release more capacity for EV integration. VSCs are used to interconnect the AC and DC distribution lines to achieve flexible power rescheduling, thus overall power flow can be optimised. An optimisation control scheme is designed based on sensitivity methods, based on which node voltages can be kept within a security range under unexpected power fluctuations of EVs.

A DC line, which is converted from an AC line, can increase maximum transfer capacity by 58.7% if using a symmetrical configuration with a neutral wire. The capabilities of distribution networks are fully utilised because more capacities are released and power rescheduling is achieved between AC and DC lines.

EV accommodation can be increased from about 87 to 235% under an 8 MW hybrid AC/DC medium voltage distribution network. About 130% of EV penetration is increased due to released capacities.

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